IMPROVED PROCEDURES FOR DETERMINING SEISMIC
SOURCE DEPTHS FROM DEPTH PHASE INFORMATION

QUARTERLY REPORT

Edward Page
Richard Houck

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Several modifications were made in the seismic source depth determination program. These modifications were directed towards improving the program's use of depth phase information, and increasing the interpretability of the final depth plot output. Two new events were run through this modified version of the program, with successful depth determinations being made in both cases.

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INTRODUCTION AND SUMMARY

In the second quarter of this contract, a final set of mod-
ifications was made to the seismic source depth determination
program, and the resulting production version was run on five new
events. The production version was decided on after development
and testing of a new data windowing technique designed to reduce
the occurrence of unwanted cepstrum peaks. Although this new
technique produced the desired results in some cases, generally
it did not work as well as the older windowing method; and, con-
sequently, the older method was the one used in the production
program. Changes incorporated in the production version include
the capability of obtaining depth plots using several different
cepstrum computation window lengths, and a peak significance level
calculation designed to assist in the interpretation of the depth
plots. Results obtained from the five new events are:

Event Date	No. of Stations Used	Depth (km)
3/27/75	4	17.5±1.5
6/30/75	5	12.5±2.0
3/7/75	2	19.5±1.5
4/28/75	2	not determined
6/1/75	3	13.5±2.0

PROGRAM DEVELOPMENT

New Data Windowing Techniques

Two new techniques for positioning the seismogram windows used in cepstrum computations were developed and tested. The principal goals of these new methods were:

1. improvement of cepstrum peaks due to depth phase correlations; and

2. reduction of spurious cepstrum peaks due to correlations between different primary phases.

The first of these new techniques consists simply of allowing windows to overlap instead of using only adjacent, non-overlapping seismogram windows. This should make it more likely that a window will exist that contains both a primary arrival and its corresponding depth phases, resulting in a cepstrum that contains the desired complete set of depth phase peaks. The second method involves defining different cepstrum computation windows for each primary phase, station, and trial depth. Each window starts at the expected primary phase arrival time and ends after the predicted arrival of the corresponding s-phase. This method guarantees that depth phases will always fall in the same window as their corresponding primary phase, and should reduce the occurrence of spurious cepstrum peaks by always using the shortest window necessary to include the complete set of expected depth phases.

The new windowing techniques were compared to the original windowing method using five different events. The results indicated that the constant length, non-overlapping windows that were originally used worked best. Although the arrival-time-controlled windows gave good results in some cases, and almost always showed some evidence of the correct depth peak, the results from the constant windows were more generally dependable. This somewhat unexpected outcome may be due to scaling inconsistencies resulting from the use of variable cepstrum computation window lengths. The basic idea behind this windowing method, however, seems to be a useful one, and it may merit further investigation at some future time.

Implementation of Production Program

Based on the results of the investigation of seismogram windowing techniques, the original version of the depth determination program was modified to serve as the production version. Two new capabilities have been added in the production program.

1. Processing of seismograms at several different cepstrum computation window lengths.

2. Determination of a significance level to be used in interpreting final depth plot output.

Previous experience has indicated that these two program features should be particularly useful in production processing of large numbers of events. Depth plot output has been found to be very sensitive to cepstrum computation window length, and the optimum window length varies unpredictably between events. Also, it

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is often not clear which, if any, of the peaks appearing on the depth plot output are meaningful. A quantitative way of estimating the significance of these peaks would be very useful to the analyst.

A technique has been implemented for estimating the significance of depth plot amplitudes and is based on the fact that these amplitudes relate to the degree cepstrum amplitudes sum when selected at lag times expected for a given source depth and epicenter distance. Therefore, one way to obtain a measure of depth plot amplitudes which would result from the analysis of seismic data containing the same spectral characteristics but not containing depth phase information, is to randomize the travel time information and reprocess a given event. In this way, one can simulate a depth plot resulting from a seismic recording in which the cepstrum peaks did not result from depth phase information and do not constructively add for travel times corresponding to any given source depth. For example, when analyzing data recorded at $\Delta = 30^{\circ}$ for a trial depth of 20 km, the program would normally add cepstrum amplitudes at delays of 5.6 seconds (pP-P), 8.3 seconds (sP-P), and 2.7 seconds (sP-pP). In computing the significance level, a depth plot amplitude at 20 km will be obtained by summing cepstrum values at three random times such as 8.1, 3.4 and 4.7 seconds. A random pick depth plot, like the one shown in Figure 1a, is constructed by making random picks like this for each depth being considered. A histogram of the random depth plot amplitudes is then constructed (Figure 1b), and a cumulative distribution function (Figure 1c) is calculated from the histogram. Finally, the amplitudes corresponding to the 80 percent and 95 percent levels on the cumulative distribution are determined and plotted on the true depth plot (Figure 1d). What is indicated by

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(a) Random Pick Depth Plot

(b) Histogram

(c) Cumulative Distribution
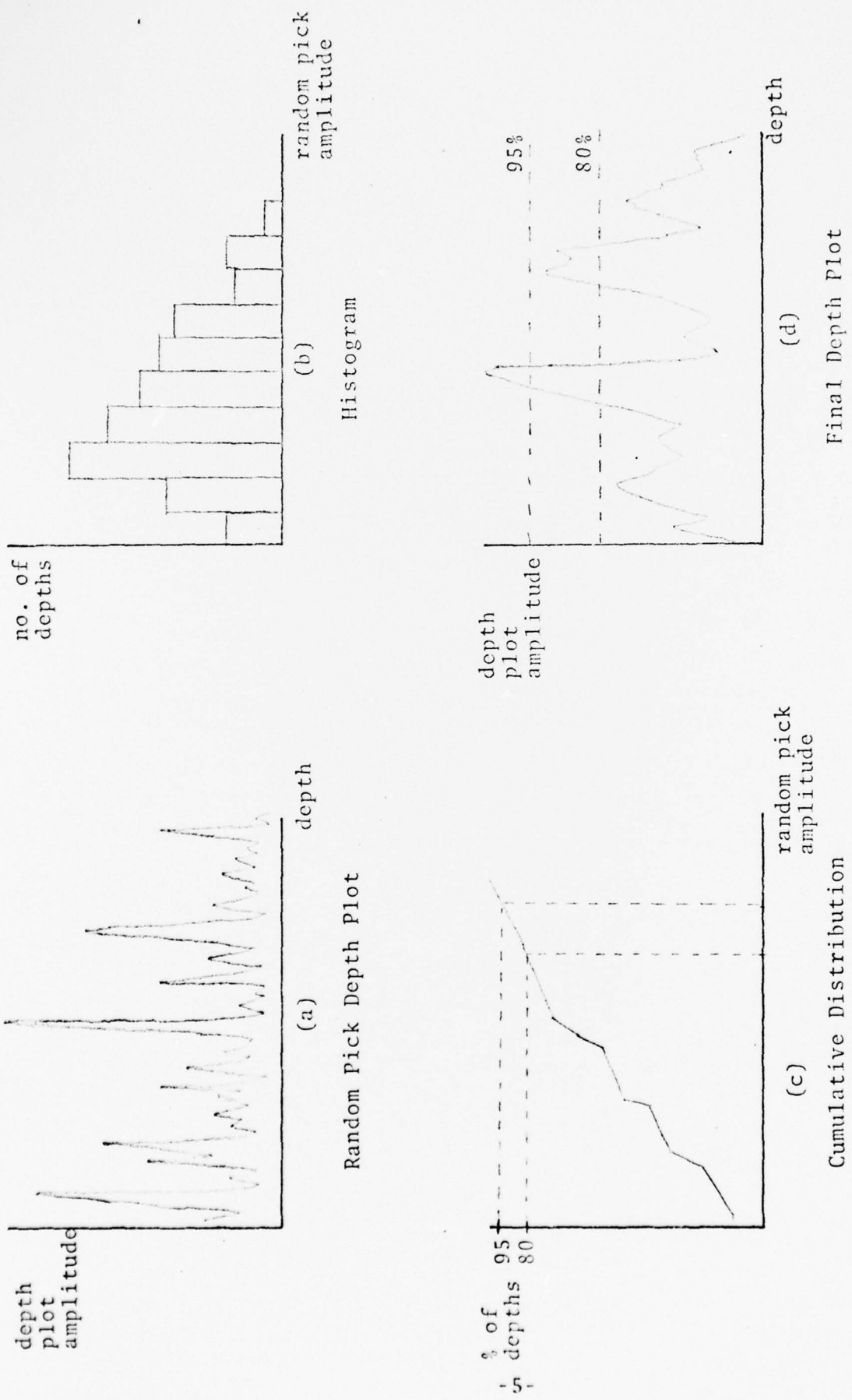
(d) Final Depth Plot

Figure 1

Peak Significance Calculation

these levels is the probability that the resulting peaks could not have been produced by chance alignment of cepstrum peaks. Thus, peaks above the 95 percent level have a 95 percent confidence that they did not occur by chance cepstrum peak alignment. However, to establish the percentage confidence of a peak above the 95 percent level relating to the correct event depth, results from a large set of events must be compiled.

NEW EVENTS

Five new events were run during this quarter, with depth estimates being successfully obtained for four of them.

3/27/75 Event (Turkey)

Seismograms from the event dated 3/27/75 (Turkey) are shown in Figure 2. The best results were obtained using the first 6.40 seconds of data from all four stations, with a 12.8 second cepstrum computation window; the resulting composite depth plot is shown in Figure 3. Interpretation was quite easy for this event, with a single dominant peak, well above the 95 percent significance level, appearing at 17.5 km. These excellent results are due to the strength of the depth phase arrivals for this event - pP can be visually detected on three of the four seismograms in Figure 2.

6/30/75 Event (Montana)

Seismograms from the event dated 6/30/75 (Montana) are shown in Figure 4. The best results were obtained using the first 51.2 seconds of data from all five stations, with a 12.8 second cepstrum computation window; the resulting composite depth plot is shown
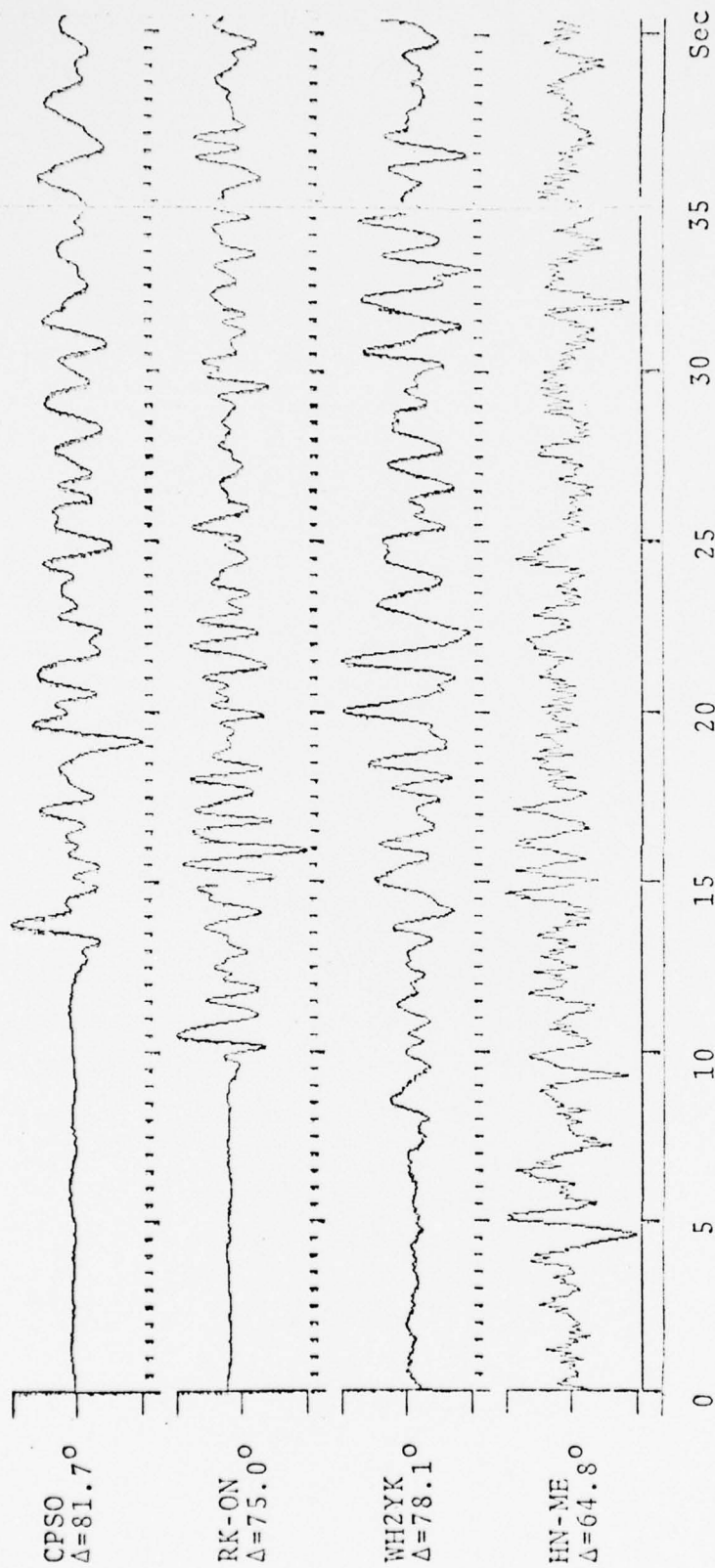
Figure 2

Turkey Event (3/27/75) Seismograms

No. of stations   = 4
Cepstrum window length = 12.8 sec
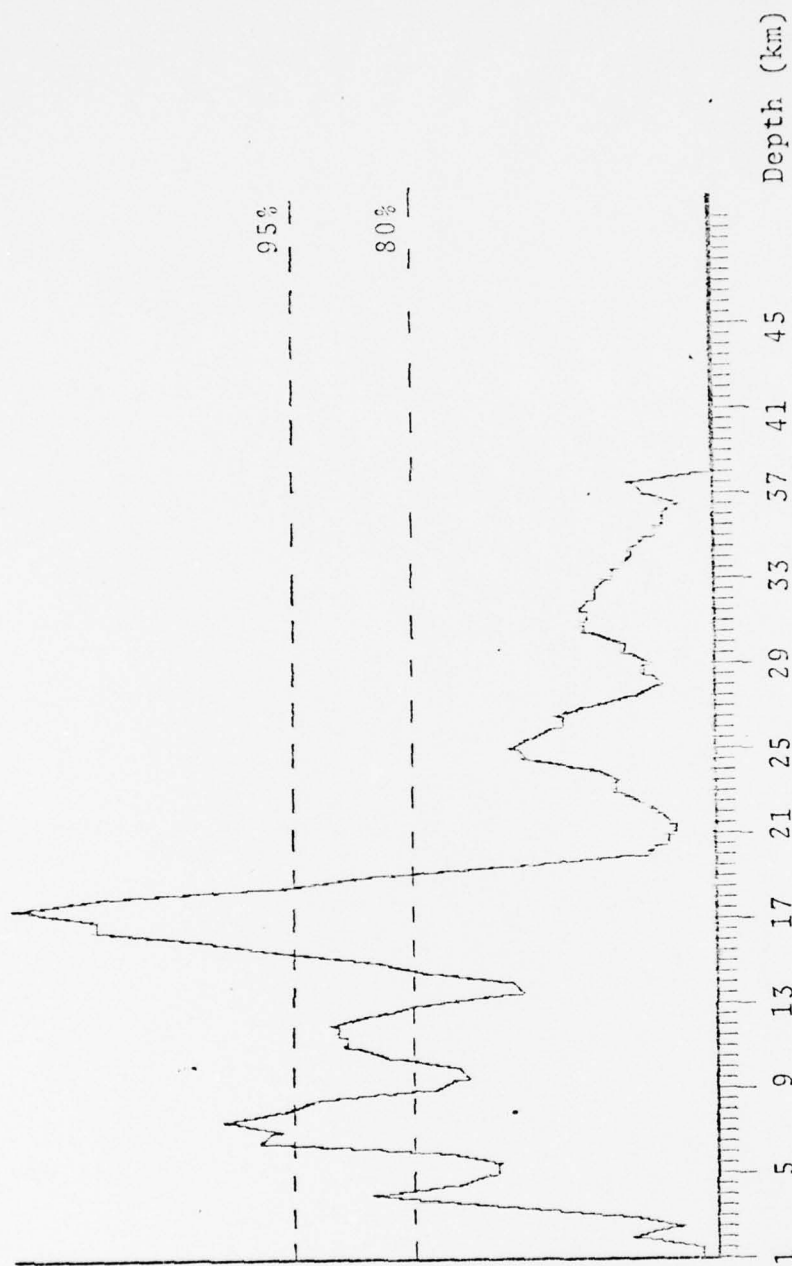Total data length   = 64.0 sec

95%

80%

Depth (km)

Turkey Event (3/27/75), Composite Depth Plot

Figure 3

CPSO
Δ=21.1°

HN-ME
Δ= 29.6°

FN-WV
Δ= 23.9°

RK-ON
Δ=12.9°
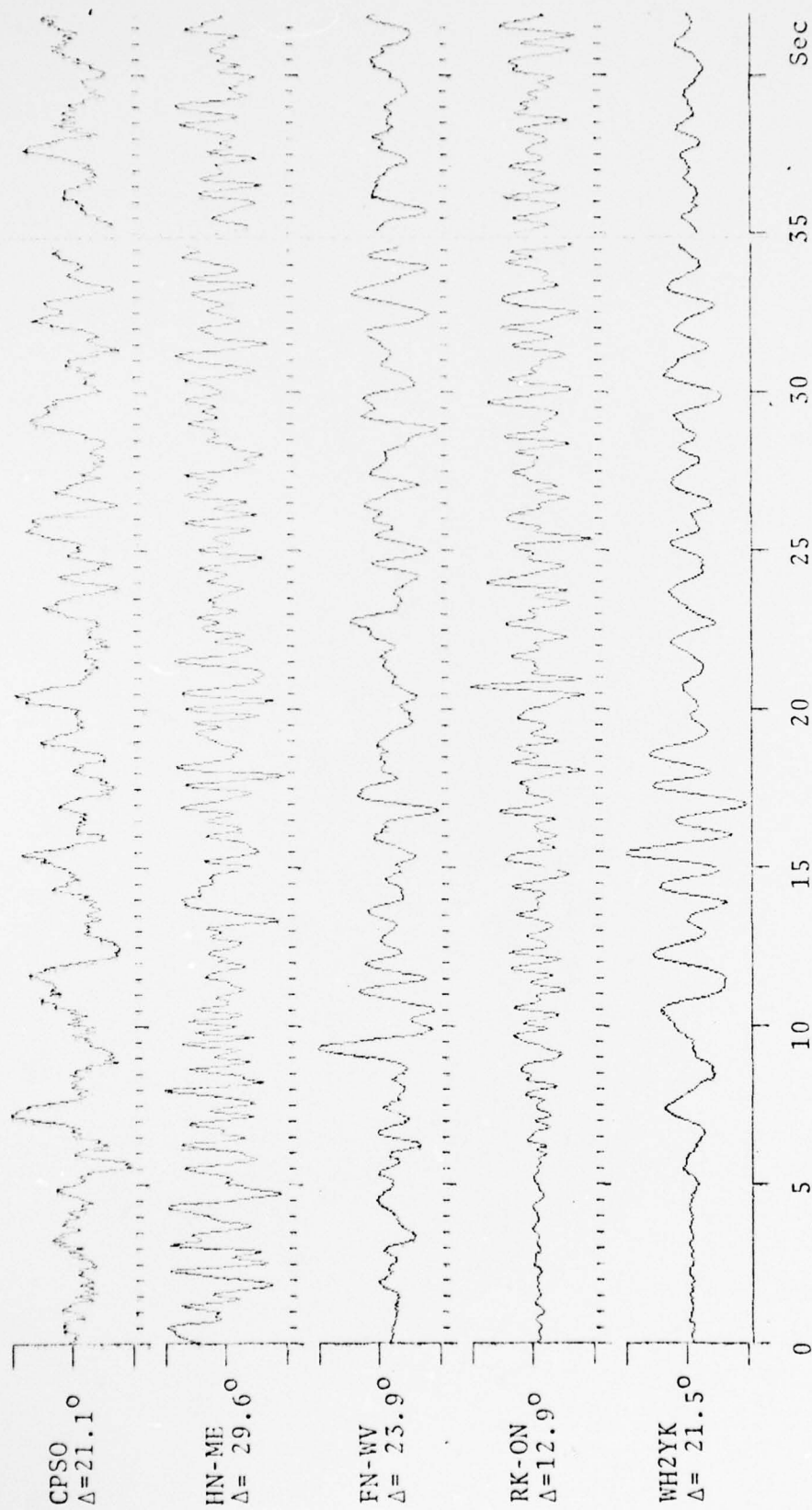
WH2YK
Δ= 21.5°

0   5   10   15   20   25   30   35   Sec

Figure 4

Montana Event (6/30/75) Seismograms

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in Figure 5. This event is not as clear cut as the previous one, but the peak at 12.5 km extends far enough above the 95 percent significance level to be picked as the correct depth. A likely explanation for the poorer quality of the depth plots obtained for this event can be found by looking at the seismograms. In contrast with the previous event, no depth phases can be seen at any of the five stations.

3/7/75 Event (Iran)

This event presented the most difficult interpretation problem of all the events in this set, and will be discussed in more detail than the others. Seismograms for this event are shown in Figure 6, and Figures 7-9 are the P, PcP, and composite depth plots obtained using 51.2 seconds of data from both stations, with a 12.8 second cepstrum computation window. From the composite depth plot alone, it appears that the peak at 8 km should be interpreted as indicating the correct depth. However, there are some problems with this interpretation. First, the height of the 8 km peak above the 95 percent significance level probably is not very meaningful, since, with only two stations being used, the statistical basis of the significance level calculation is not very good. Second, the P-phase depth plot shows no single dominant peak, and the PcP plot shows that the 8 km peak on the composite plot comes from the reinforcement of the strong 8 km PcP peak and the much weaker 8 km peak seen on P. This reinforcement is not, in this case, indicative of a depth-consistent cepstrum peak. At the large Δ's being considered, P and PcP are being picked from the same cepstrums and have the same delay times, so any peaks occurring in the first cepstrum computation window (used to generate

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No. of stations   = 5
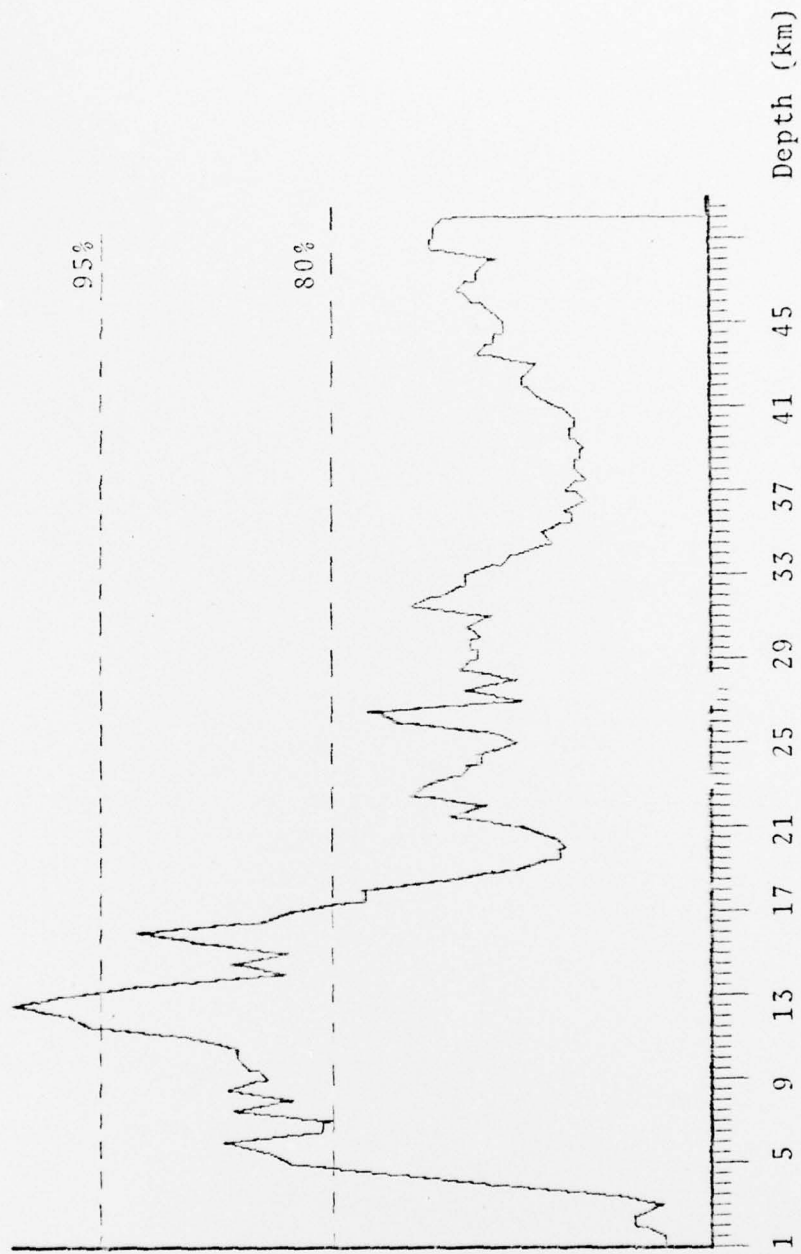Cepstrum window length = 12.8 sec
Total data length   = 51.2 sec

95%

80%

Depth (km)

1 5 9 13 17 21 25 29 33 37 41 45

Figure 5

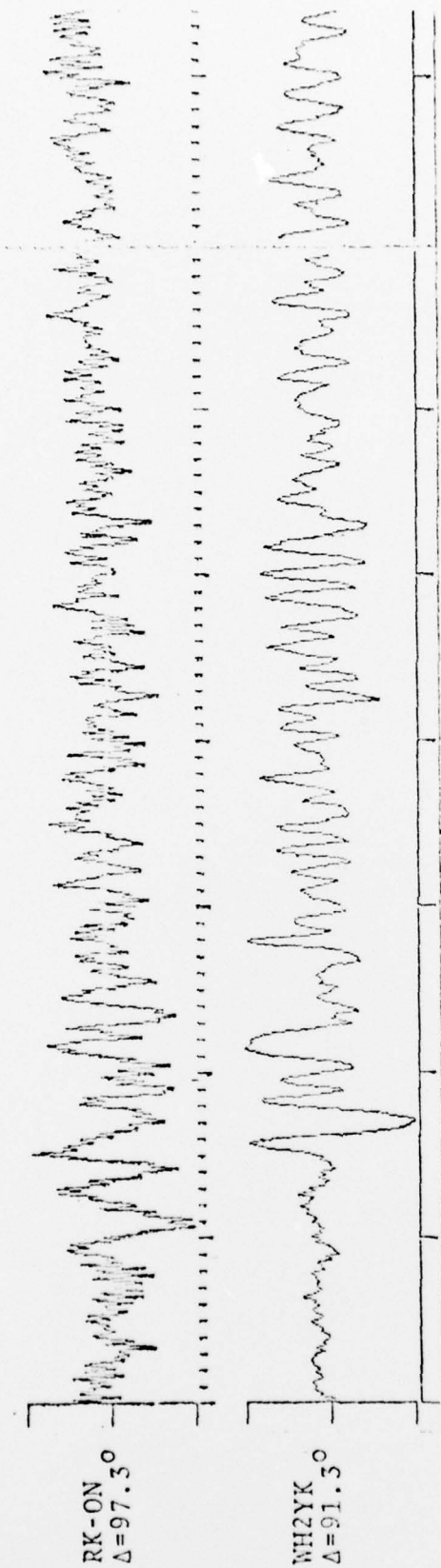Montana Event (6/30/75), Composite Depth Plot

RK-ON
Δ=97.3°

NH2YK
Δ=91.3°

Figure 6

Iran Event (3/7/75) Seismograms

No. of stations   = 2
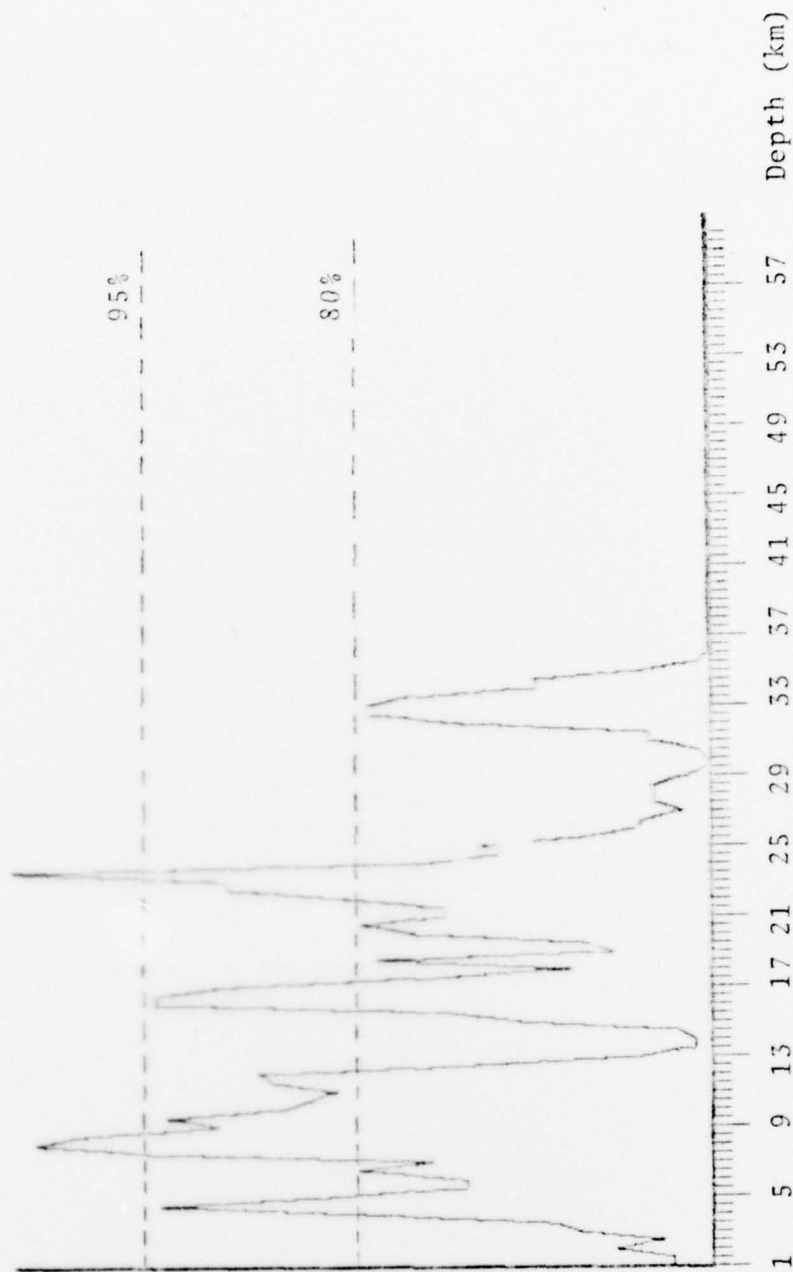Cepstrum window length = 12.8 sec
Total data length   = 51.2 sec

95%

80%

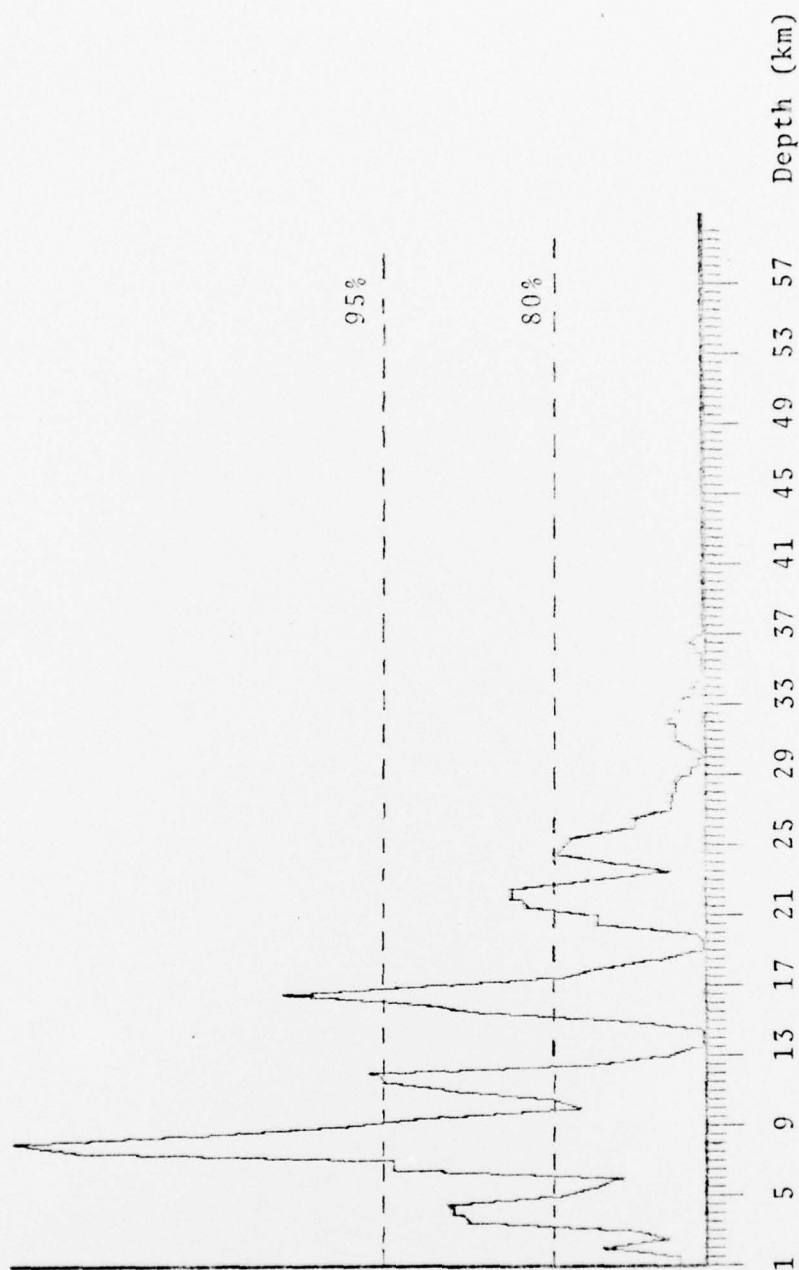1   5   9   13 17 21 25 29 33 37 41 45 49 55 57   Depth (km)

Figure 7

Iran Event (3/7/75), P Depth Plot

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No. of stations   = 2
Cepstrum window length = 12.8 sec
Total data length   = 51.2 sec

Figure 8

Iran Event (3/7/79), PcP Depth Plot

No. of stations   = 2
Cepstrum window length = 12.8 sec
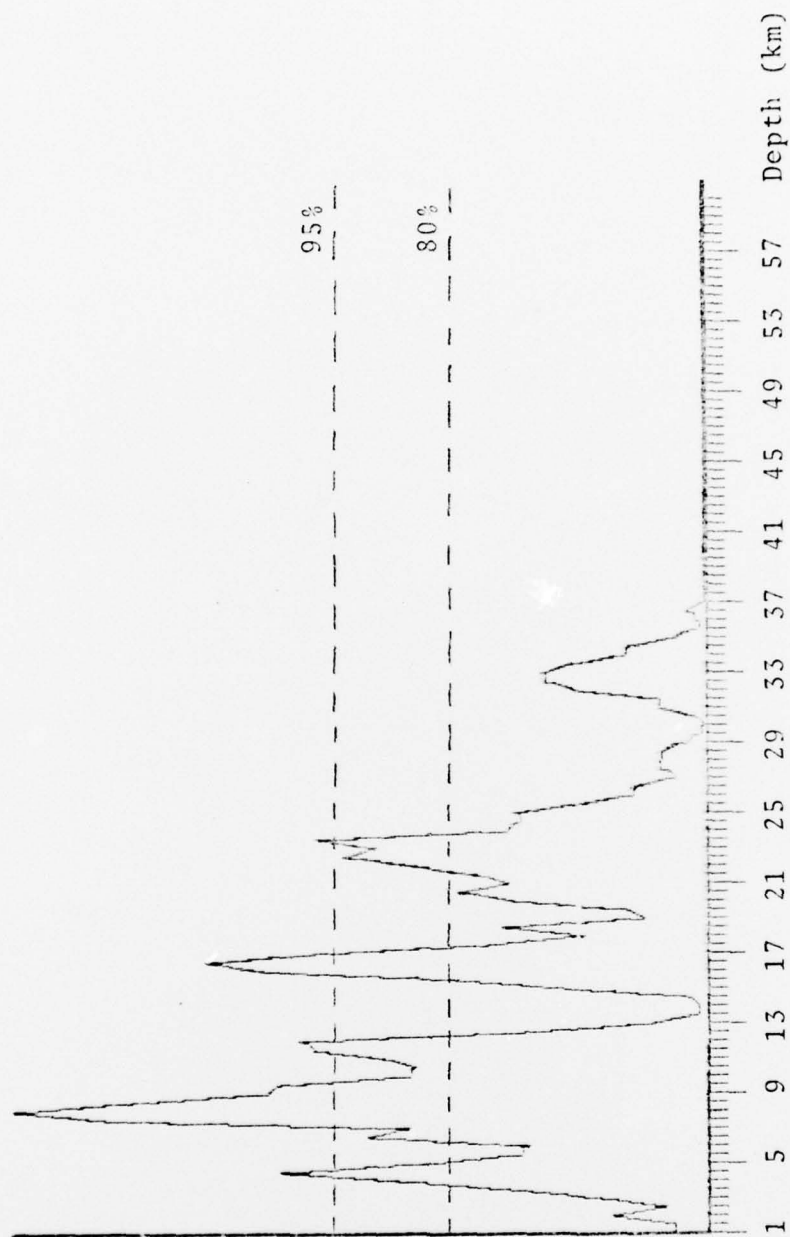Total length   = 51.2 sec

95%

80%

1 5 9 13 17 21 25 29 33 37 41 45 49 53 57   Depth (km)

Figure 9

Iran Event (3/7/75), Composite Depth Plot

both P and PcP depth plots) will be enhanced over peaks from later cepstrums (used only for P plot). Consequently, the composite will contain peaks that have been unfairly reinforced, and only the P depth plot will be useful for interpretation.

A better result was obtained when the same data was processed with a 25.6 second cepstrum computation window. The P depth plot, shown in Figure 10, has a single dominant peak at 19.5 km, which can justifiably be interpreted as indicating the correct depth. The success of the depth determination program for this event is encouraging in view of the small number of stations used and the lack of visually detectable depth phases on the seismograms.

4/28/75 Event (Kasmir)

This event is the only one of the five events processed for which no depth determination could be made. The seismograms are shown in Figure 11. Like the Iran event, both stations have large Δ's, so only the P depth plots are likely to be useful. The P depth plot obtained using 51.2 seconds of data from both stations, with a cepstrum computation window of 12.8 seconds is shown in Figure 12. A peak is present at 17 km, but its low significance level makes it unacceptable. Figure 13 is the P plot from the same data, with a 25.6 second cepstrum computation window. There is a strong peak present at 4 km, but this depth represents a pP-P time of about one second, which is too short to be detected using present methods.

No. of stations = 2
Cepstrum window length = 25.6 sec
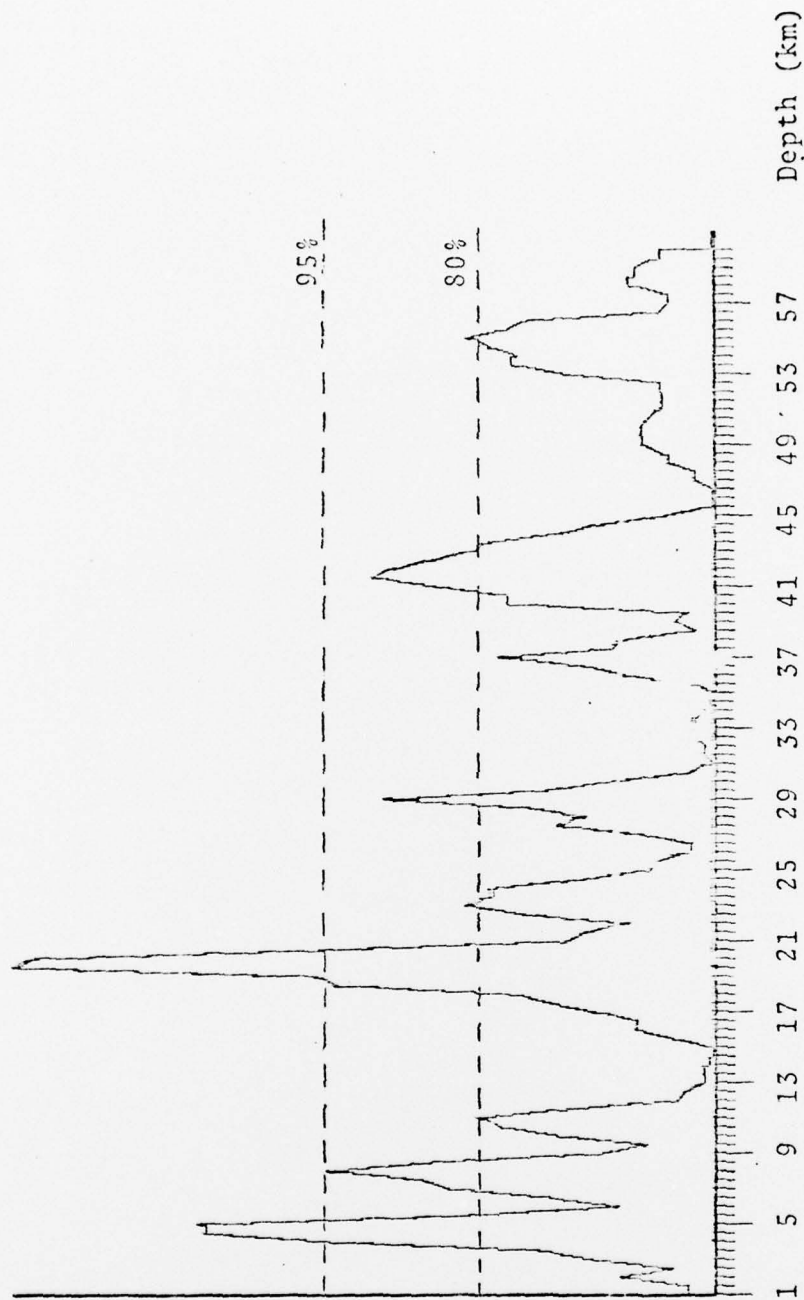Total data length = 51.2 sec
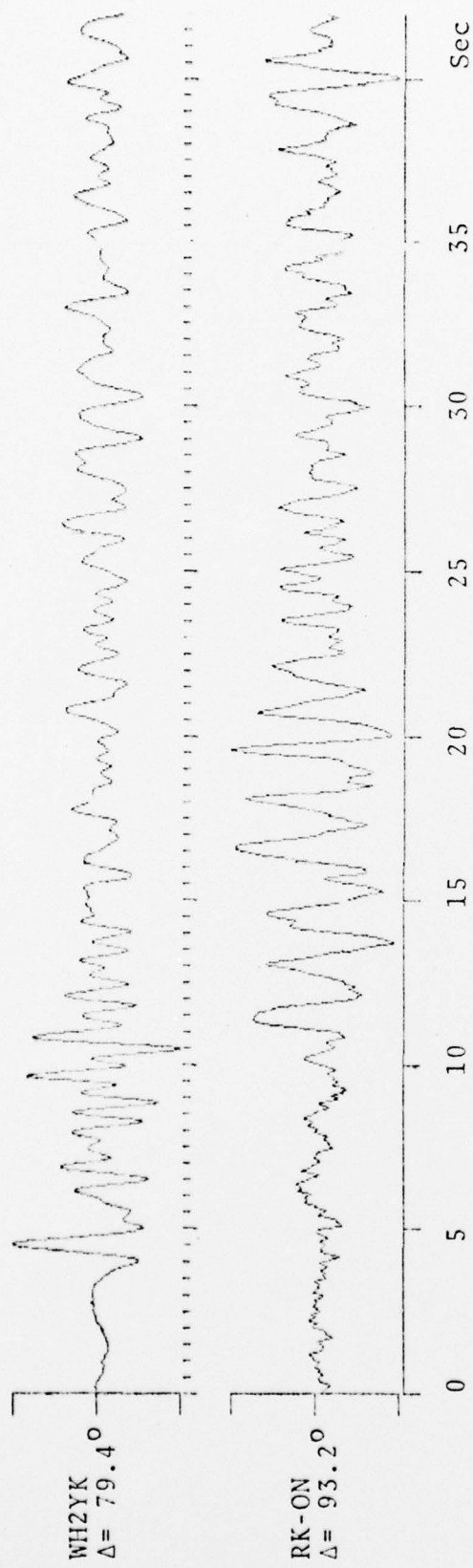
Figure 10

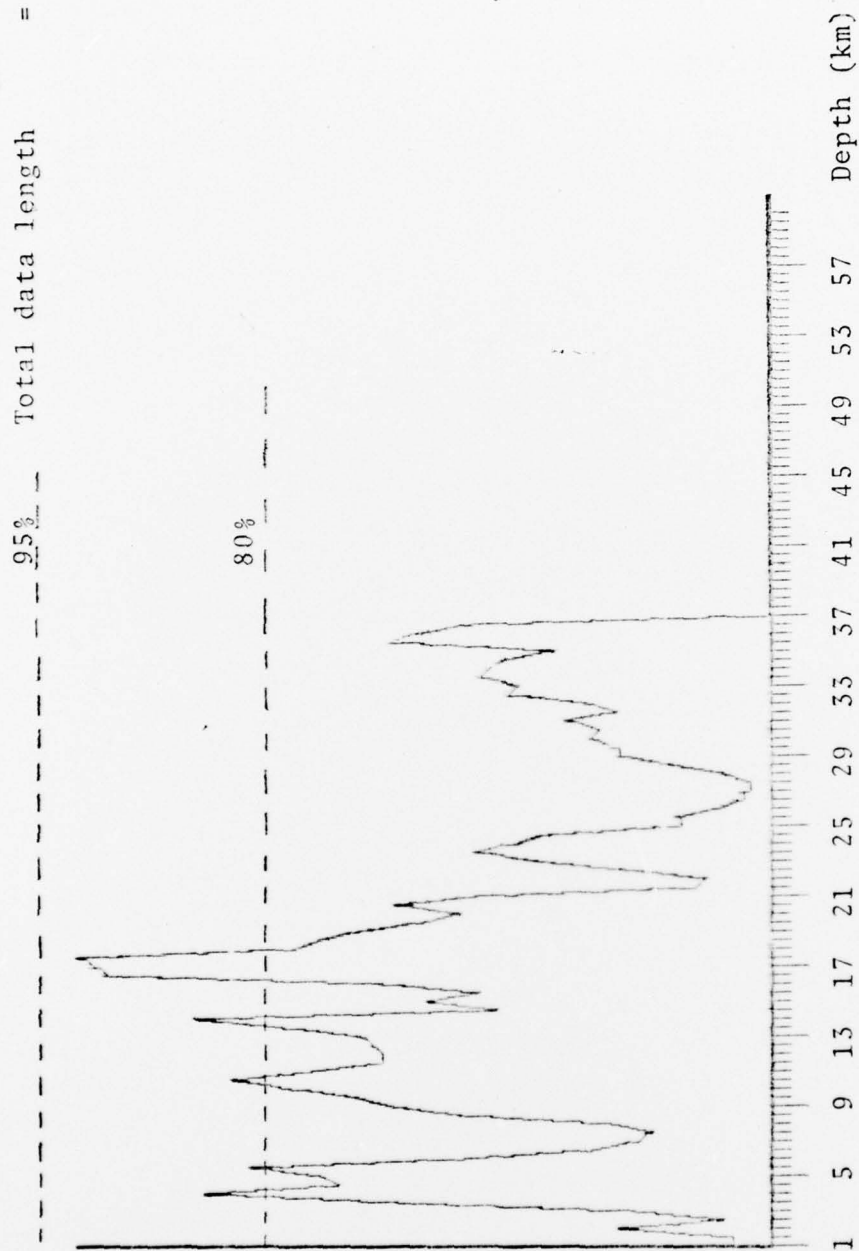Iran Event (3/7/75), P Depth Plot

Figure 11

Kasmir Event (4/23/75), Seismograms

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Figure 12

Kasmir Event (4/28/75), P Depth Plot

No. of stations = 2
Cepstrum window length = 25.6 sec
Total data length = 51.2 sec

95%

80%

Depth (km)

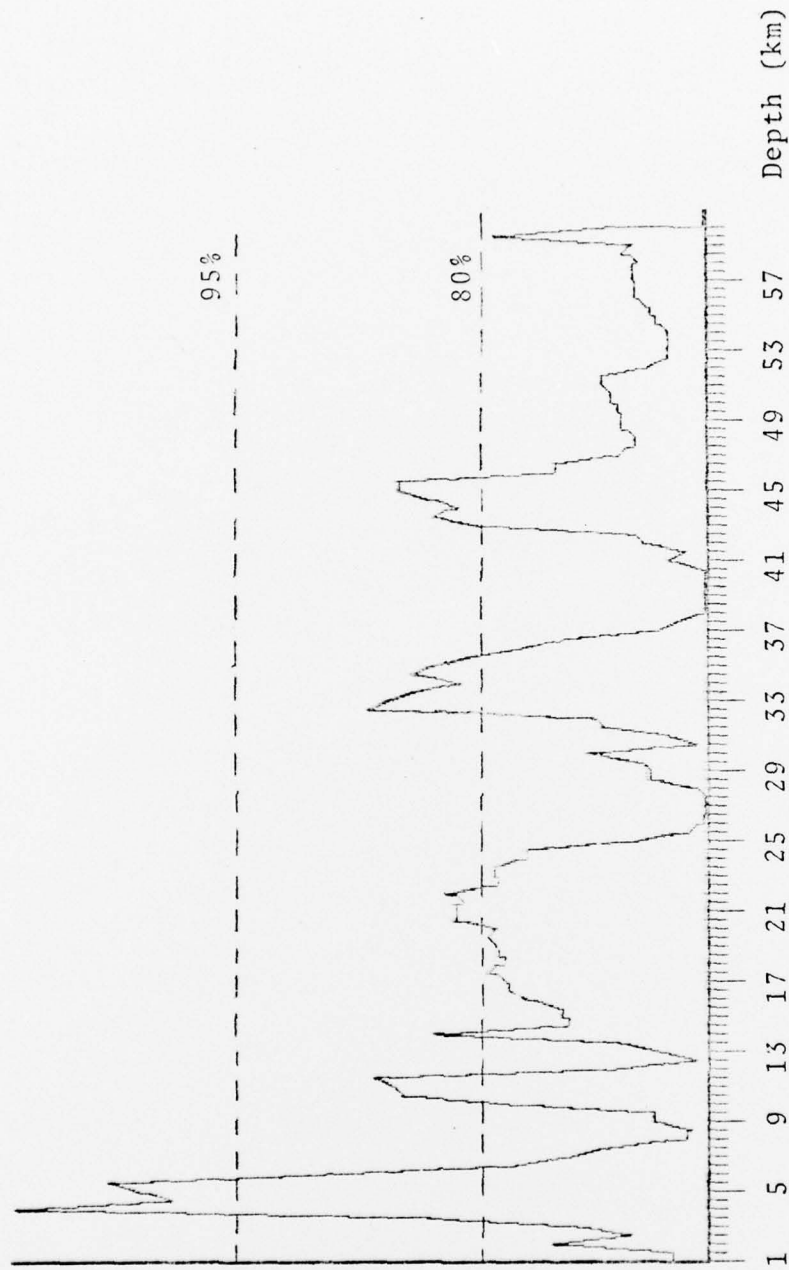1 5 9 13 17 21 25 29 33 37 41 45 49 53 57

Figure 13

Kasmir Event (4/28/75), P Depth Plot

6/1/75 Event (Mojave Desert)

Seismograms for this event are shown in Figure 14. Best results were obtained using a 12.8 second cepstrum computation window on 76.8 seconds of data from all three stations; the composite depth plot is shown in Figure 15. The dominant peak at 13.5 km is well above the 95 percent significance level, and was interpreted as indicating the correct depth.

Conclusions From Analysis of New Events

Several conclusions can be drawn from the depth determination program results for these five events.

- Results from the Turkey and Mojave Desert events show that source depths from the depth determination program agrees with those obtained by observing pP on the seismograms when pP is visible.

- Results from the Montana and Iran events demonstrate that source depth estimates can be obtained even when no depth phases are visible.

- Evidence to date indicates that analysis involving fewer than three stations significantly reduces the probability of obtaining a depth estimate.

- The computation of significance levels appears to be a very useful technique and should be investigated further.
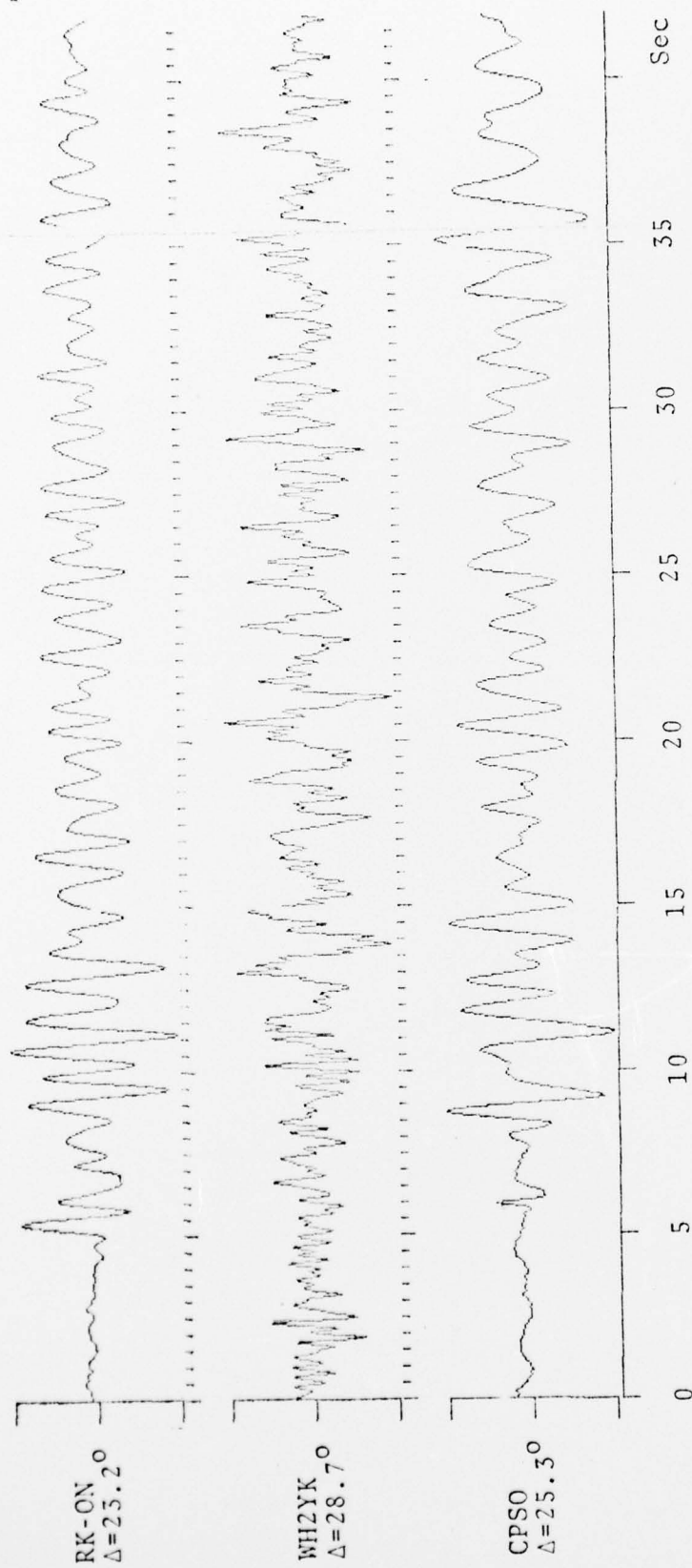
Figure 14

Mojave Desert Event (6/1/75), Seismograms

No. of stations   = 5

Cepstrum window length = 12.8 sec
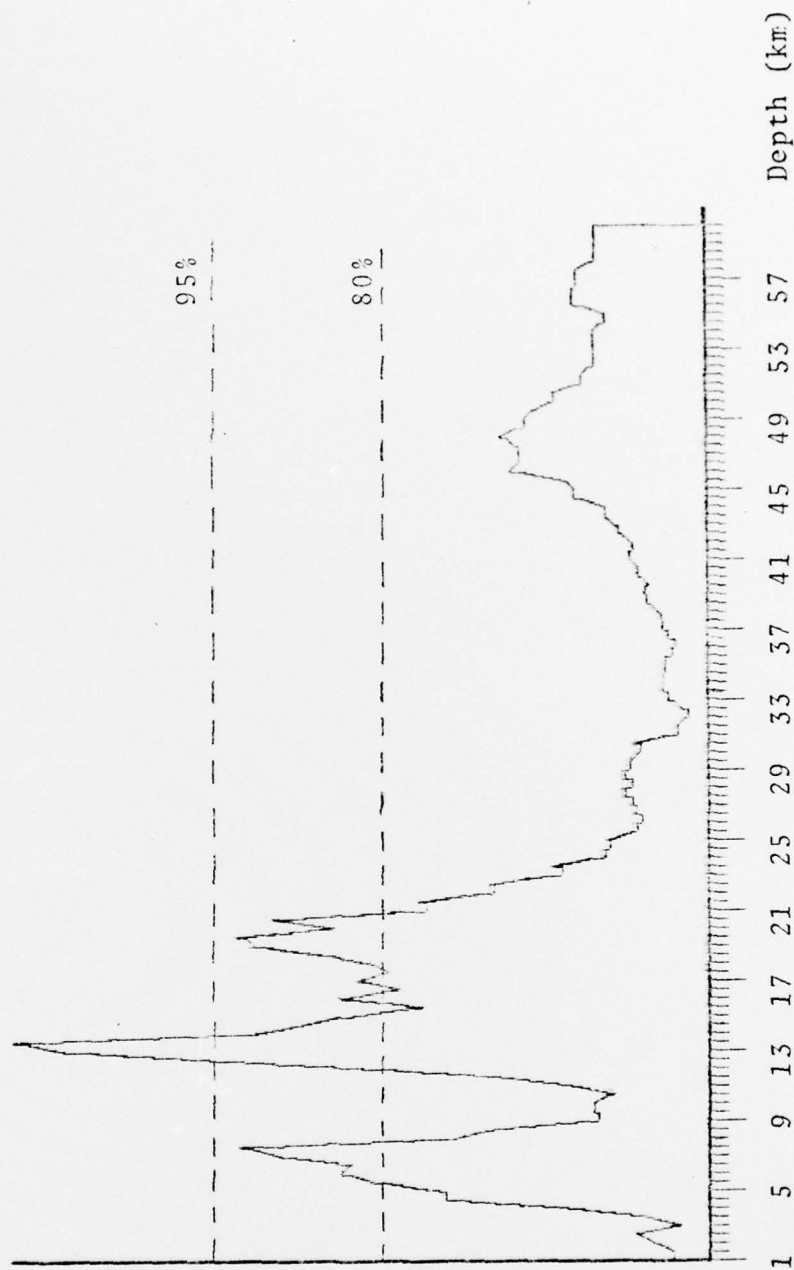
Total data length   = 76.8 sec

95%

80%

Depth (km)

1   5   9   13 17 21 25 29 33 37 41 45 49 53 57

Figure 15

Mojave Desert Event (6/1/75), Composite Depth Plot

FUTURE PLANS

In the remainder of this contract, we plan to process the 15 station Andreanof Island event (11/22/65) in several subsets to further investigate the effects of the number of stations used. Any new events that are provided will also be run. Results from all the events that have been processed will be analyzed for the effects of number of stations, seismogram signal-to-noise ratio, and station Δ's.

In the area of program development, present results indicate the need for future work in two areas. First, improvements in the determination of peak significance may be possible. For example, meaningful estimates of significance levels approaching 100 percent may be possible if some kind of curve fitting is done on the random pick cumulative distribution function. Second, techniques for eliminating cepstrum peaks due to non-depth phase spectrum structure need to be explored. This may eliminate the shallow depth "noise" observed on many depth plots, and aid in the detection of shallow depth earthquakes.